LIDAR and Numerical Modeling Studies of Small-Scale Lateral Dispersion in the Ocean

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Award Number: N00014-09-1-0194

LONG-TERM GOALS

Our long-term goal is to better understand lateral mixing processes on scales of 0.1-10 km in the ocean. This includes the underlying mechanisms and forcing, as well as the temporal, spatial, and scale variability of such mixing. The particular goal of the present work is to directly observe the processes governing lateral stirring at these scales via high resolution dye release experiments using airborne LIDAR. The broad impacts of this research range from a better understanding of ocean ecosystems and ocean health, to improved parameterizations in numerical models, to a variety of other practical purposes.

OBJECTIVES

This annual report marks the end of year 1 of a 5 year study as part of the "Scalable Lateral Mixing and Coherent Turbulence" (a.k.a., LatMix) DRI. The goal of the present work is to conduct a series of dye release experiments in the seasonal pycnocline and upper ocean to understand lateral dispersion and frontal processes on scales of 10 m to 10 km. The main effort of the present work is a collaboration between J. Ledwell and E. Terray (WHOI), M. Sundermeyer (UMass Dartmouth), and J. Prentice and B. Concannon (NAVAIR).

This project is being performed jointly with a collaborative NSF grant to J. Ledwell, E. Terray, and M. Sundermeyer (see "Related Projects" below). ONR is providing support for the airborne LIDAR operations, and is supplementing our efforts in the field and in analysis under the NSF support.

APPROACH

The vertical and horizontal dispersion and advection of dye release experiments will be monitored on spatial scales of meters to several kilometers in the horizontal, 1-10 meters in the vertical, and on time scales of minutes to hours, up to 4 days. Sampling of the dye will be performed using airborne LIDAR, as well as *in situ* sensors lowered and towed from a ship. Additional measurements of optical characteristics, hydrography, currents, and internal wave characteristics will be used to identify

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **LIDAR and Numerical Modeling Studies of Small-Scale Lateral Dispersion in the Ocean**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Massachusetts Dartmouth,School for Marine Science and Technology,706 South Rodney French Blvd,New Bedford,MA,02744-1221**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

particular driving mechanisms of the observed dispersion. The dye experiments will be coordinated with AUV and microstructure measurements by other investigators to discern forcing mechanisms responsible for the dispersion. The dye experiments will also be guided by numerical modeling process studies by other investigators under the DRI, and will provide data for testing such models.

In the context of the DRI modeling efforts, M. Sundermeyer is also collaborating closely with M.-P. Lelong in support of her DRI grant, "LES Modeling of Lateral Dispersion in the Ocean on Scales of 10 m – 10 km." As part of this, numerical simulations and analysis are being performed under the present effort in preparation for, and to aid interpretation of, the main field studies. These numerical simulations are also being coordinated with modeling efforts of other DRI participants.

WORK COMPLETED

An engineering field test was conducted in September, 2008, and was reported on in our FY08 annual report under grant number N00014-08-1-0545. A second, more extensive engineering field test / pilot cruise will be conducted in spring, 2010, with the main field efforts to be conducted in summer 2011 and 2012.

Our main efforts in the current reporting year have been to continue our analysis of the 2008 engineering test, and to plan for upcoming field efforts in 2010, 2011, and 2012. To this end, we have completed the following work:

1.) We participated in planning meetings for the LatMix DRI in Monterey in Dec, 2008 and in Chicago in June 2009. We also continue to exchange information with other DRI participants toward planning and coordinating LatMix field efforts, numerical modeling studies, and theoretical analysis. As part of this, we recently produced a draft Site 1 field / cruise plan which was circulated to all DRI participants. We also continue to examine possible field sites for the main Site 1 field experiments.

2.) We have begun planning an engineering field test / pilot cruise for Spring 2010. Participants will include the WHOI and UMass dye PIs, the NAVAIR LIDAR group, the UMass AUV group (Goodman), and possibly other DRI participants.

3.) We continue to work with the NAVAIR LIDAR group, led by Drs. Jennifer Prentice and Brian Concannon, to identify system parameters for their new LIDAR system that optimally enable them to detect and map fluorescent dye patches. Modifications of their LIDAR system are planned for winter 2009, and will be tested as part of the 2010 field tests / pilot study.

4.) Under separate funding (DURIP and collaborative NSF – see "Related Projects" below), we have begun to acquire new field instrumentation that will be used in the upcoming LatMix DRI / NSF field experiments. This includes a SATLANTIC Apparent Optical Properties System, a Sea Sciences Acrobat tow sled, and a new micro CTD and fluorometer sampling package for small-scale surveys of the dye patches.

5.) We continue to explore and develop improved methods for inverting LIDAR waveforms to obtain absolute dye concentrations following our work under previous funding (Terray et al., 2005; Sundermeyer et al., 2007). This includes consideration of LIDAR system characteristics, and ocean optical properties, including effects of multiple scattering. Our primary efforts thus far have been to review the LIDAR literature, and to better understand the constraints associated with the improved methods.

6.) As part of the modeling efforts in collaboration with M.-P. Lelong, we continue to conduct numerical simulations pursuant to one of the hypotheses of the LatMix DRI, involving localized internal wave breaking and subsequent lateral stirring by the relaxation of diapycnal mixing events. During the current reporting year we have focused primarily on better understanding the details of such wave breaking and the mixed patches themselves, with the goals of better understanding the processes leading to sub-mesoscale lateral dispersion. These simulations will also guide field efforts in distinguishing among different possible lateral mixing processes.

RESULTS

Our engineering field test was conducted in September, 2008, and was reported on in our FY08 annual report under grant number N00014-08-1-0545. Subsequent analysis of data from those tests revealed that:

- The dye signal for the LIDAR will be quite strong at 20 m depth and may well be detectable beyond 50 m depth in clear water.
- It is possible to deploy too much dye - blocking the deeper waters from the light. The experiments must be planned accordingly.
- The aircraft navigation system must be in better condition than it was for the pilot experiment in order to efficiently survey a dye patch. NAVAIR and the pilot are aware of this and claim that their nav system was not its usual self for the experiment.

A second engineering field test / pilot cruise will be conducted in spring, 2010, with the main field efforts to be conducted in summer 2011 and 2012. Further field results will follow those efforts.

Regarding our modeling work, simulations have been performed to re-examine internal breaking at critical layers in order to determine the amount of excess momentum generated by an impinging wave. Further simulations have been conducted to examine the propagation, deformation, and breaking of a nonlinear wave packet through an ambient linear stratification. In both cases, momentum, total potential energy, and available potential energy have been analyzed in an attempt to quantify the breaking, and to understand the detailed nature of the diapycnal mixing events whose adjustment are believed to lead to lateral dispersion.

Our main conclusion thus far for the critical layer experiments is that such a scenario, while interesting and relevant to the ocean, is not the most relevant to the problem at hand, namely, lateral stirring by small-scale vortices caused by patchy mixing. The reasons for this are two-fold. First, while plane waves do result in wave breaking at critical layers, they do not represent localized breaking events in the horizontal dimension. As such, we believe that the breaking they produce is not conducive to adjustment and formation of small-scale vortices leading to lateral stirring. Second, even if the breaking waves did result in localized mixed patches, we believe the large shears associated with the critical layers would result in shear dispersion that would dominate the lateral dispersion compared to any eddy stirring effects.

Regarding the wave packet experiments, our findings thus far are that localized wave packets do break in isolated regions, causing localized mixing; and that these breaking regions mediate a net momentum flux in the direction of the wave (Fig. 1). Supportive to these findings, we have also found that Thorpe's (1999) prediction of the horizontal velocity of the breaking region appears to hold for packets of low steepness waves, while his prediction of $c_b = c_g + c_p$ does not hold for packets of high steepness waves. One difficulty in these simulations, similar to the critical layer simulations, is discerning the effects of mixing itself from the direct signal associated with the internal waves. This distinction is made particularly difficult by the fact that the wave packet, through natural dispersion and wave breaking, also changes shape over the course of the simulation. To isolate the effects of mixing, we thus have used density following Lagrangian particles to visualize regions of mixing (Fig. 2). This technique clearly shows the isolated nature of the mixed patches, and we thus believe it will help isolate the motion associated with the waves from the effects of the breaking itself.

In our ongoing analysis of the breaking of isolated wave packets, we plan to continue to examine the evolution of the total kinetic and available potential energy associated with wave breaking. By examining the relationship between the total mixing and the spatial distribution of both the mixing and velocity defects, we will formulate a simple description of how this process can be parameterized into our ongoing vertical mode stirring simulations. This will thus help our ongoing simulations to be more realistic, and provide further answers as to the efficacy of this mechanism of lateral dispersion.

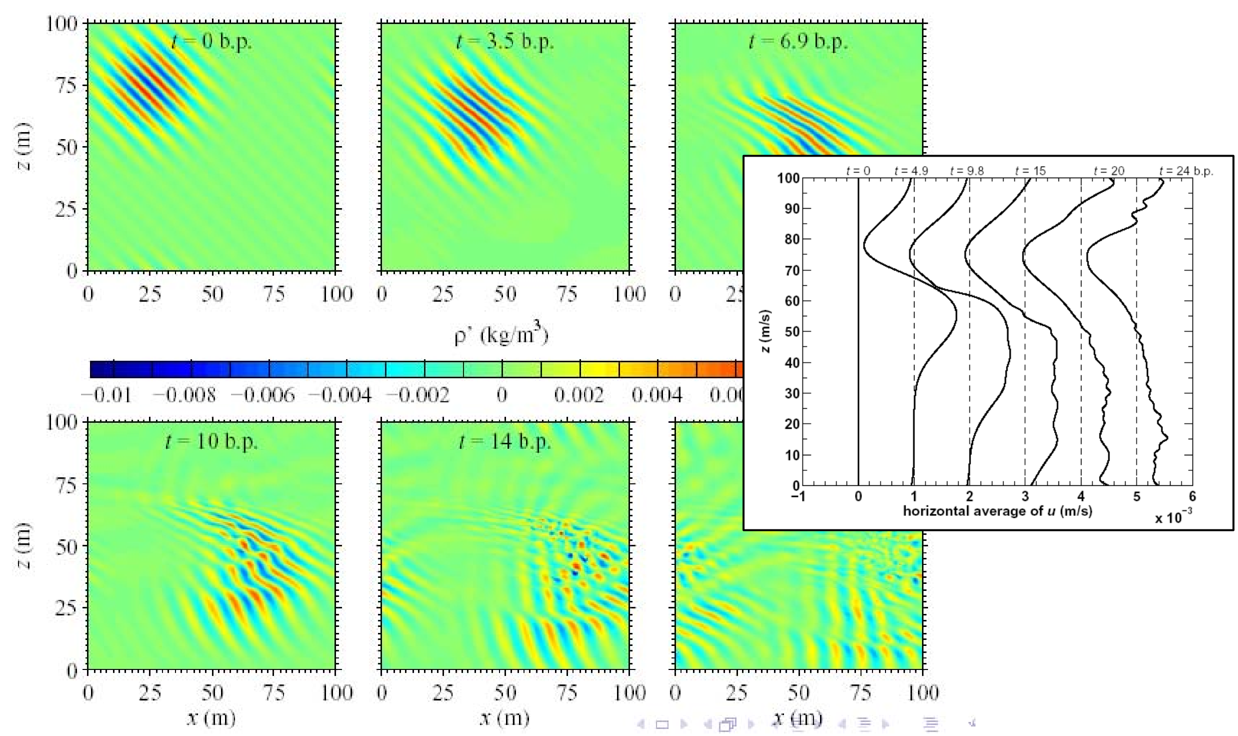

Figure 1. Example simulation of wave packet breaking and dispersing in model domain. Time from top left to bottom right is given in buoyancy periods (b.p.). Inset shows horizontal average of horizontal velocity, u (m/s), for approximately the same times.

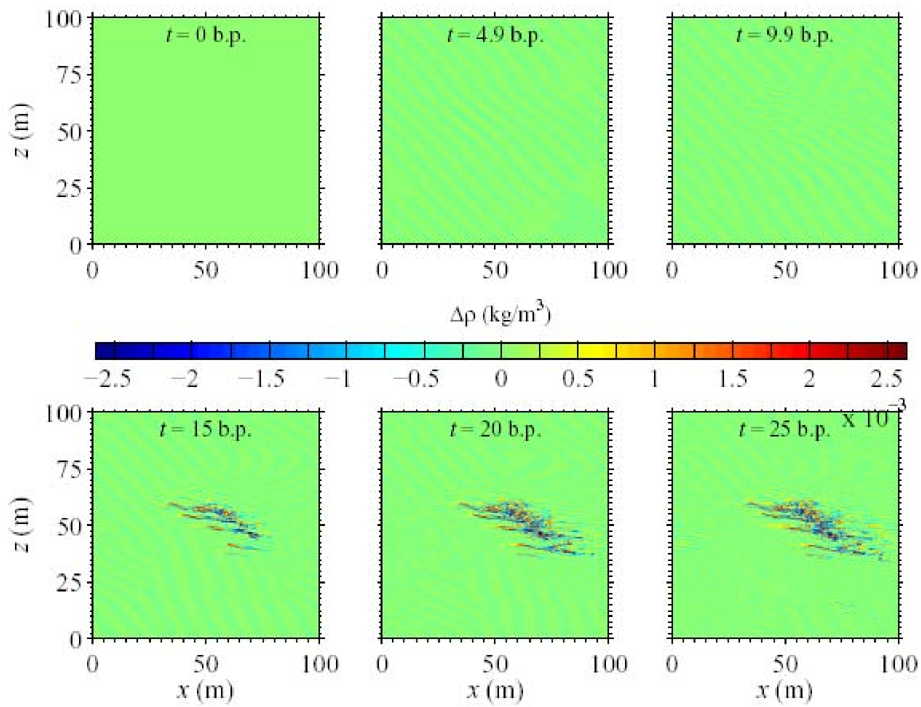

Figure 2. Example of change in density following Lagrangian particles seeded throughout the model domain. Time from top left to bottom right is given in buoyancy periods (b.p.).

RELATED PROJECTS

The above work and findings represent a joint effort on the part of LatMix DRI PIs Ledwell and Terray (WHOI) and Sundermeyer (UMass Dartmouth) under ONR grants N00014-09-1-0175 and N00014-09-1-0194, respectively.

Field instrumentation to be used in the upcoming DRI field work is being purchased in part under DURIP grant N00014-09-1-0825, and in part under a related NSF project entitled "Collaborative Research: LIDAR Studies of Lateral Dispersion in the Seasonal Pycnocline", NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI).

The PIs efforts under the ONR LatMix DRI are being performed in coordination with the PIs efforts under the above mentioned NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI).

The numerical simulations described here are also supported in part under a related NSF project entitled "Numerical Simulations of Small-Scale Stirring Internal Waves, Diapycnal Mixing and Horizontal Finestructure," NSF Award #OCE-0623193; Co-PIs M.A. Sundermeyer (UMass Dartmouth) and M.-P. Lelong (Northwest Research Associates).

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